Materials and Design 52 (2013) 337–344

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Formability of Ti–6Al–4V titanium alloy sheet in magnetic pulse bulging

Fen-Qiang Li *, Jian-Hua Mo, Jian-Jun Li, Liang Huang, Hai-Yang Zhou

State Key Laboratory of Material Processing and Die and Mould Technology, Huazhong University of Science and Technology, Wuhan 430074, People's Republic of China

ARTICLE INFO

Article history:
Received 7 April 2013
Accepted 20 May 2013
Available online 30 May 2013

Keywords:
Ti–6Al–4V titanium alloy sheet
Magnetic pulse forming
Formability
Strain rate

ABSTRACT

In order to investigate the formability of Ti–6Al–4V titanium alloy sheet in high speed forming process, electromagnetic forming (EMF) namely magnetic pulse forming with an Al driver sheet is performed experimentally. Formability under EMF is compared with that in quasi static condition. Fracture analysis for the titanium alloy Ti–6Al–4V is then carried out to study the fracture mechanism and material response. Results indicate that the formability undergoing EMF process with a driver sheet is increased beyond that exhibited in quasi-static tests. In electromagnetic free bulging, the forming limit of Ti–6Al–4V increases by 24.37%, which is more optimistic than AA5052-O. Fractography analysis using SEM determines that the Ti–6Al–4V titanium alloy sheet fails in a combination of ductile fracture and shear fracture when subjected to the electromagnetic bulging process while only ductile fracture develops in quasi-static condition.

1. Introduction

Formability is the inherent ability of material to form different shapes under a certain forming process. It is one of the most important features of metal forming. Formability employing a conventional forming regime is a function of a number of factors such as material properties (e.g. strain hardening coefficient, strain rate sensitivity, anisotropy ratio) and process parameters (e.g. strain rate, temperature).

Ti–6Al–4V alloy finds a wide variety of uses, especially in the aircraft industry because of a remarkable combination of characteristics in terms of high mechanical properties, elevated corrosion resistance and low density. The importance of this material is testified from the fact that it covers more than 50% of the titanium alloy industrial production. Two main problems hinder wider application of the alloy. Titanium alloy exhibits lower formability compared to carbon steel. In addition, titanium alloy manifests serious Bauschinger effect and severe springback due to its high yield strength and low Young's modulus.

Over a number of decades, it has been known that pulsed forming technologies such as electromagnetic forming (EMF), explosive forming (EF) and electrohydraulic forming (EHF) have the potential to increase sheet metal formability beyond conventional limits. A very detailed review of these technologies was reported by Psyk et al. [1] and Mynors and Zhang [2]. The issue of the lower ductility of the light alloys potentially can be resolved by some combination of traditional press stamping operations and pulsed forming processes. Opinions on the extent of formability improvement made possible by pulsed forming vary as reported in recent research literature.

Very optimistic improvement of formability in pulsed forming compared to traditional forming limit diagram (FLD) by a factor of 5.5 for AA6061-T4, a factor of 3.5 for interstitial free (IF) iron and a factor of 3.0 for copper were found out through carrying out EHF forming of the flat sheet into a conical die [3,4]. Through accelerating flat steel blanks by flat EMF coils towards axisymmetric (missile shaped) and wedge shaped punches, much more aggressive improvement of formability varying from a factor of 4 to a factor of 20 was reported [5]. The low carbon, low alloy steels that derived their strength from cold rolling achieved approximately the same level of elongation although they had different levels of formability in quasi static conditions. A substantial, but much more moderate improvement in formability in pulsed forming was reported where the pulsed forming results were compared to low speed dynamic deformation and quasi static forming conditions: the increase of formability in pulsed forming was much higher than in low speed dynamic forming [6].

In light alloys, the formability of aluminum alloy AA5754 and AA6111-T4 by Imbert et al. [7] and Golovashchenko [8], AA5052-O by Liu et al. [9], and AA5182-O by Oliveira et al. [10], as well as magnesium alloy AZ31 by Meng et al. [11] and Xu et al. [12] and AZ31B-O by Jimbert et al. [13] and Ulacia et al. [14] under electromagnetic forming or electrohydraulic forming had been reported, exhibiting an improvement in forming limit compared to that in quasi-static. As of yet, very limited information is known on the high-velocity formability of titanium alloy sheet, such as Ti–6Al–4V. Takahashi et al. [15] reported incremental improvement in the forming limit of Titanium plate under dynamic

* Corresponding author. Tel.: +86 13397127373; fax: +86 27 87557174.
E-mail addresses: lfq@hust.edu.cn (F.-Q. Li), mjh@mail.hust.edu.cn (J.-H. Mo), ljj@263.net.cn (J.-J. Li).

0261-3069/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.05.064

bulging; while El-Magd and Abouridouane [16] reported a decrease of the deformation at fracture for a compressed sample of Ti–6Al–4V wrought alloy up to $10^3\ s^{-1}$. The formability performance in pulsed forming of Ti–6Al–4V titanium alloy sheet, in comparison with its quasi static performance, will be reported in this paper. Since this material has relatively high strength and low electrical conductivity, EMF technology cannot be employed effectively without using a highly conductive driver material, as reported by Seth et al. [5]. Therefore, an Al driver sheet was used to force the forming of Ti–6Al–4V in this research.

Apart from improving the formability of material at room temperature, the electromagnetic forming (EMF) process has many other advantageous characteristics. These include high efficiency, light equipment, the need for only a single die and a reduction in both warping and springback. EMF is safe and stable. Compared with explosive forming (EF), it is easy to control the discharge energy, and organize and operate production during process. Therefore, EMF is the main concern in this study.

In this paper, the objective of this study is to report the results of formability testing of Ti–6Al–4V in EMF and quasi static condition and to provide an explanation of the observed formability improvement based on fracture analysis and material response through SEM.

2. Experimental set-up

2.1. Materials

The light alloy used in this experiment is titanium alloy Ti–6Al–4V (annealed), which is used widely in the manufacture of aerospace structures to take advantage of its high strength and excellent corrosion resistance. The chemical composition of Ti–6Al–4V is given in Table 1.

Before beginning the experiment, the surface of the sample was cleaned using acetone. Clear touching circular grids with 2.5 mm in diameter were then printed on it using the Lectroetch electrochemical marking equipment (MODEL V-45A), with the aid of a special electrolyte. After electromagnetic bulging, the circular grid distorted into an ellipse shape. The corresponding major and minor strains could be thereby calculated by measuring the length of the major and minor axes of the ellipse respectively. Strain values were measured by ASAME Target Model (version 4.1).

2.2. Capacitor bank

A commercial Xi'an XD Power capacitor bank was used. It includes four capacitors, 160 μF each, connected in parallel. Ignitrons switch their connection to the electrical bus with the coil. The maximum energy of the bank is 200 kJ when the charge voltage is 25 kV. In this study, only two out of the four capacitors were connected in serial. So the maximum available discharge energy of the bank was 25 kJ. The charge voltage was varied to control the discharge energy.

2.3. Coil

A 72-turns flat spiral coil was used in electromagnetic bulging, as shown in Fig. 1. The flat spiral coil was tightly wound with enameled copper wire coated with glass fiber, the outer layer of which was sealed and reinforced using phenolic resin. The overall size of the coil was φ180 mm in planar, 100 mm in height. The inner diameter of the wire portion was φ10 mm and the outer diameter was φ100 mm, four layers in the height. The specimen, when placed on top of the potted coil, was approximately 2 mm above the top of the copper windings.

Fig. 1. Flat spiral coil.

2.4. Die

A die with a φ100 mm open-round window and an entry radius of 10 mm was used in electromagnetic bulging to provide the biaxial tensile strain state, as shown in Fig. 2. A hemispheric punch with a diameter of φ20 mm was used in the Erichsen test.

2.5. Driver sheet

Results of experiments in the literature [17] indicate the use of a driver sheet made of a lightweight and easily deformable material improves the energy efficiency of the coil, particularly in the forming of high resistivity material. To this end, considering that the resistance of Ti–6Al–4V is equal to 169.3 μΩ cm [18], an aluminum alloy AA5052-O sheet with a φ5 mm center hole was used to drive Ti–6Al–4V in the forming process. Mechanical properties and parameters of the driver sheet are listed in Table 2. Besides, use of the driver sheet can also improve the force suffered by the coil and extend its life.

2.6. Method

During the electromagnetic free bulging of titanium plate, an aluminum plate was placed between a titanium plate and the coil, as shown in Fig. 3. The titanium plate was supported by a perforated epoxy ring. The hydraulic machine pressed the die, which was placed on the workpiece, to prevent the flow of sheet metal. A pulse current was generated in the coil after discharging the capacitor, and then a repulsive force was developed between the coil and the sheet metal, to force deformation of the sheet. By adjusting the discharge voltage, the voltage which initiated the cracks could be determined and the ultimate strain on the sheet at that voltage measured.

Table 1
Chemical composition of the titanium alloy Ti–6Al–4V.

Element	Ti	Al	V	Fe	C	N	H	O	Other
Weight (%)	Base	6.07	3.99	0.04	0.01	0.01	0.015	0.12	Total<0.40 (each<0.10)

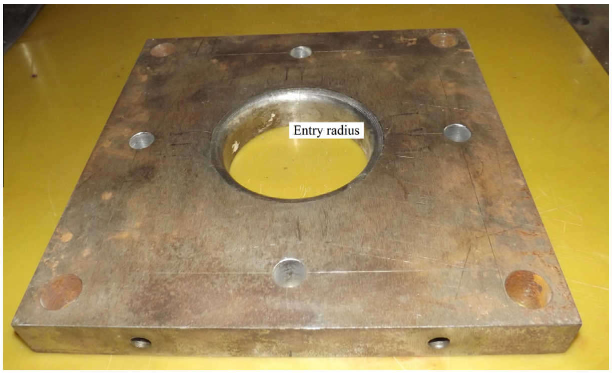

Fig. 2. Die for electromagnetic free bulging.

Table 2
Mechanical properties and parameters of the driver sheet.

Material	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Thickness (mm)	Resistivity (μΩ cm)
AA5052-O	87	198	22	2	2.7

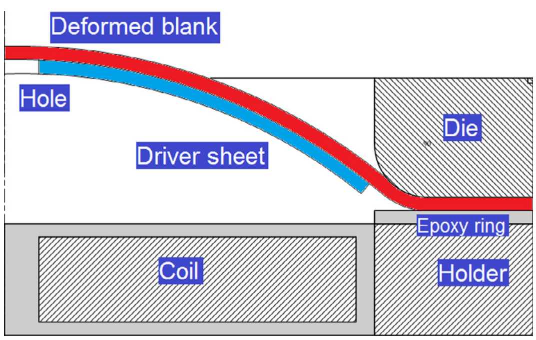

Fig. 3. Configuration of EMF for Ti–6Al–4V.

2.7. Ultimate strain measurement

When the discharge energy exceeded the critical value for the sample, a crack developed. If the energy is increased further, the sample will break into several pieces, limiting the ability to measure the ultimate strain. After obtaining the optimal parameter for the driver sheet, the discharge voltage was tune to determine the critical discharge energy value. In this study, the values were: discharge voltage $U = 25$ kV and capacitor $C = 80$ μF. The current over time was traced by a Pearson current sensor and a digital oscilloscope, as shown in Fig. 4. The rise time of discharging current is $t = 290.8$ μs, peak current is $I_{max} = 5360$ A and angular frequency is $\omega = 5401.64$ rad/s. Using the principle of conventional forming limit diagram, the strain near the crack area was measured.

3. Results

3.1. Tensile test

The mechanical properties of a material, such as yield strength, tensile strength and elongation rate can be obtained using the quasi static tensile tests. In this study, all the tensile specimens were prepared following the quasi static tensile specimen standard [19], as shown in Fig. 5. It should be noted that, for this paper the elongation was obtained by measuring the deformed grid on the specimen. The uniaxial tensile test of Ti–6Al–4V titanium alloy sheet was carried out on the computer controlled electronic universal testing machine (Zwick/Roell Z010) and the results are listed in Table 3. It can be observed that Ti–6Al–4V has very high yield strength and low yield rate, exhibiting low ductility.

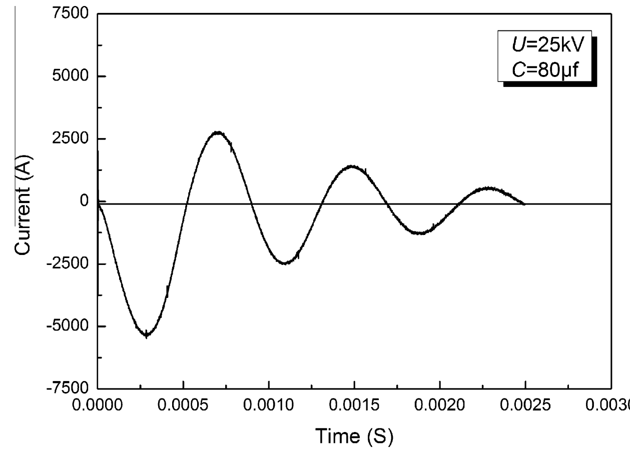

Fig. 4. Measured current vs. time profile.

3.2. Erichsen test

The forming limit of a material under the quasi static state can be obtained using the standard Erichsen test. In order to obtain different strain states, different sizes of samples were used here, as shown in Table 4. The deformed samples after Erichsen test using a hemispheric punch with φ20 mm in diameter are shown in Fig. 6. Fig. 7 is the Forming Limit Diagrams (FLD) of titanium alloy Ti–6Al–4V in the quasi static condition. The solid symbols represent the data obtained from the Erichsen test with different dimensions in width. The open symbols represent the data obtained from tensile testing. The solid line is the forming limit curve, representing the outer envelope of the data. When the strains after deformation are above the curve, the workpiece cannot be formed safely in the quasi static condition. It can be observed that the formability of Ti–6Al–4V is poor in the quasi static condition. In plane strain state, the largest safe strain is only 4.63%.

3.3. Electromagnetic bulging test

Fig. 8 is the ultimate strain graph of titanium alloy Ti–6Al–4V illustrating results of both the quasi static condition and electromagnetic bulging. The size of the sample used to measure the strains in electromagnetic bulging is 180 × 200 mm, and the strains of the sample with 40 × 90 mm in quasi static condition are chosen to be compared with because the minor strains in both conditions are nearly the same. The ultimate strain values reached using electromagnetic bulging are significantly higher than those resulting in the Erichsen test, as indicated in Fig. 8. In electromagnetic bulging, the major and the minor strains are of 9.04–9.57% and 2.68–2.97% respectively. In the Erichsen test, the major strain of 7.51–8.41% and the minor strain of 2.65–3.31% are obtained. An increase in the major strain of approximately 24.37% is thus achieved with EMF compared to those reached using the quasi-static condition. Fig. 9 is the forming limit of Ti–6Al–4V both under the electromagnetic bulging process and the Erichsen test. The curve represents the forming limit in quasi static condition and

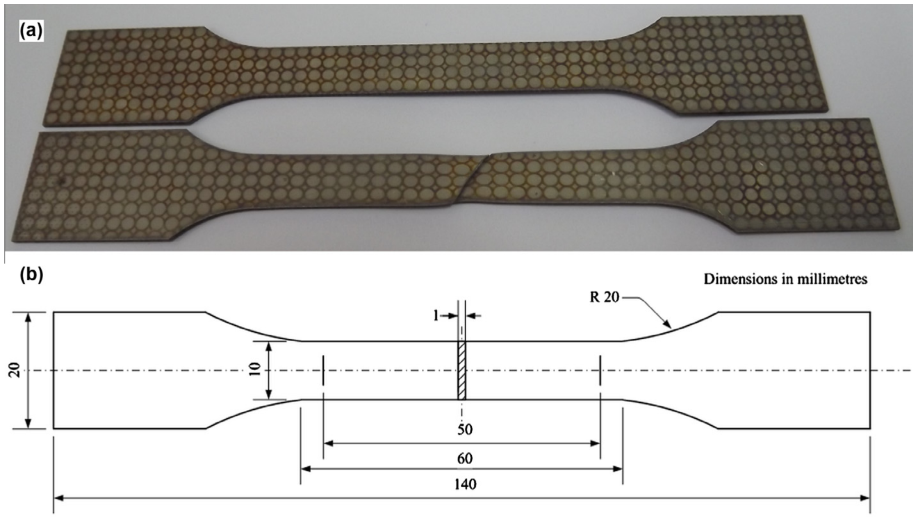

Fig. 5. Tensile samples (a) shapes before and after test, (b) dimensioned schematic.

Table 3
Properties of Ti–6Al–4V at room temperature.

Material	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Thickness (mm)	Resistance (μΩ cm)
Ti–6Al–4V	1000	1040	11.52	1	169.3

Table 4
Dimensions of titanium alloy samples (unit: mm).

Length × thickness	90 × 1						
Width	30	40	45	55	65	75	90

the solid symbols represent the forming limit using electromagnetic bulging. It can be also observed that the forming limit increases by 24.37% for Ti–6Al–4V in a biaxial tension state.

According to the literature [20], the different deformation velocities resulted from the different discharge voltages had different effects on the deformation. In order to estimate the deformation velocity of workpiece, a proven methodology described in the literature [21] was used to simulate the process. The used parameters were all consistent with the experimental parameters as given in Section 2. The simulated results indicate that the maximum deformation velocity in the center of the workpiece is 164.72 m/s which occurred at 267 μs after discharging, while the maximum deformation velocity at a point on workpiece corresponding to 1/2 the radius of the coil is 85.64 m/s, as shown in Fig. 10.

The Erichsen test and EMF process were also used to determine formability of AA5052-O sheet (also used as a driver sheet when forming Ti–6Al–4V) for comparison with the results obtained with Ti–6Al–4V. The combined Erichsen test and EMF formability results for AA5052-O are shown in Fig. 11. The curve is the forming

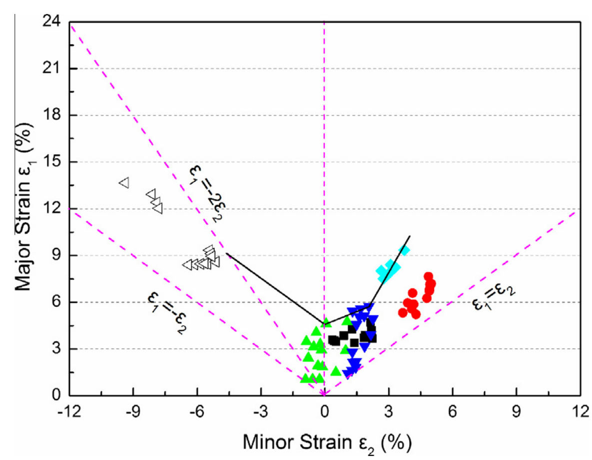

Fig. 7. Forming limit diagram of titanium alloy in quasi static condition.

limit of AA5052-O in the quasi static condition provided by Hecker [22], and the symbols are the experimental data. The solid symbols are the data obtained from the tensile test and Erichsen test while the open symbols are the results obtained by EMF. As indicated in Fig. 11, the forming limit of AA5052-O increases by only 10.97% over the Erichsen test when electromagnetic free bulging is used.

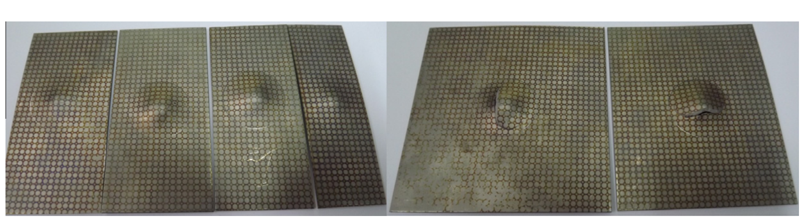

Fig. 6. Dome shapes after Erichsen test.

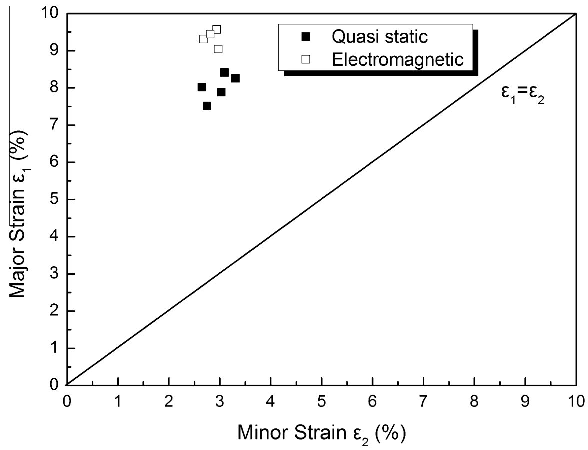

Fig. 8. Results on formability of Ti–6Al–4V sheets in quasi static and EMF.

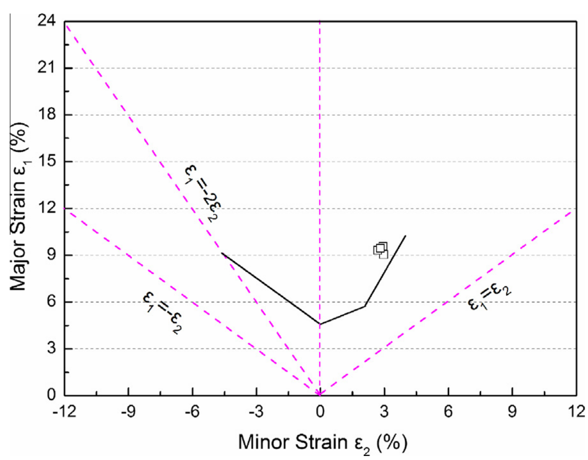

Fig. 9. Combined Erichsen test and EMF formability results for Ti–6Al–4V.

Though the forming limit of aluminum alloy AA5052-O is about 5 times that of titanium alloy Ti–6Al–4V in the quasi static condition, the improvement in forming limit for Ti–6Al–4V is more optimistic than AA5052-O in EMF process. The reason may be found in the difference in the structures of the two materials. Aluminum alloy is a face centered cubic (FCC) structure while titanium alloy is a

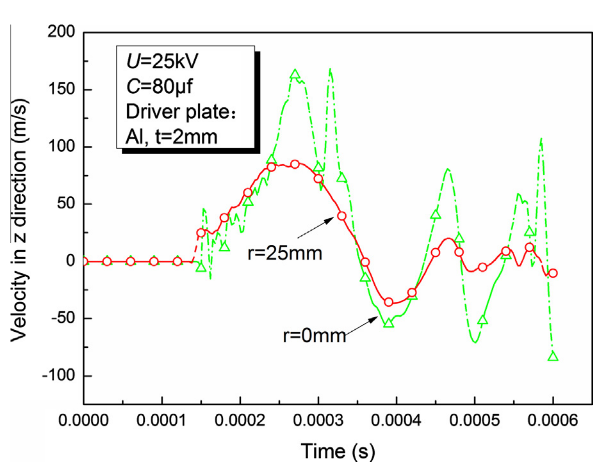

Fig. 10. The deformation velocity at different radii on the workpiece as a function of time.

close-packed hexagonal (HCP) structure. Investigation of that issue is beyond the scope of this paper and invites further research.

Fig. 12a and b illustrate two failure modes in titanium alloy Ti–6Al–4V and aluminum alloy AA5052-O that result when subjected to the electromagnetic bulging process. Cracking of the titanium alloy starts in the dome when failing, while the fracture location in the aluminum alloy is in the side wall, a distance removed from the dome. This is closely related to the microstructures and formability of the two materials. The main factors extending the forming limit of aluminum alloy in the condition of electromagnetic forming as well as the fracture mechanism had been studied in detail by Imbert et al. [23]. They reported that parts formed with the EMF process did not fail in pure ductile failure, but rather in a combination of plastic collapse, shear fracture and ductile failure as determined by fractographic analysis. The fracture mechanism of titanium alloy will be discussed in the next section of this paper.

3.4. Fracture analysis

Fracture samples in electromagnetic forming and the Erichsen test are shown in Fig. 13. The expanding behavior of the crack when undergoing electromagnetic bulging and Erichsen test can be observed from the figures. In the Erichsen test, a crack appears at the top of the sample, while in the electromagnetic forming process, secondary cracks develops along the main crack. In Fig. 13a, the upper right corner is the partial enlarged view of the crack. The specimen undergoing electromagnetic bulging developed a main crack, which spawned additional secondary cracks. Only a single crack developed in the sample undergoing the Erichsen test, as shown in Fig. 13b. Two different fracture behaviors are apparent in the macroscopic morphology of the crack in the lower right corner of the figures. The crack resulting from EMF is characterized by a 45° inclination in about half the thickness and a V-shaped pit in the remaining thickness, as shown in Fig. 13a. In the Erichsen test the crack is characterized by a 45° inclination throughout the thickness, as shown in Fig. 13b.

The scan photos of fractography in Fig. 14 reveal that in the electromagnetic bulging the fracture morphology is irregular while that in the Erichsen test is relatively regular. In electromagnetic bulging the fracture is characteristic of shear band and dimple with only dimple in the Erichsen test material.

The scanning morphology of the fracture zone, as shown in Fig. 15, shows that in electromagnetic bulging, the dimple of material fracture is deeper than that in the Erichsen test (quasi-static), indicating that titanium alloy Ti–6Al–4V has better formability in electromagnetic bulging. Moreover, the dimples in electromagnetic bulging are the uniform equi-axed dimples, as shown in Fig. 15a, while those produced in the Erichsen test are arranged in a certain direction, as shown in Fig. 15b.

4. Discussion

According to the Wood's report [24], the formability of titanium alloy Ti–6Al–4V was significantly improved in the dome bulging, when the rate of bulging exceeded a certain speed, as shown in Fig. 16. The conclusion is verified by our work with electromagnetic bulging of Ti–6Al–4V and the result obtained in this study is consistent with his conclusion.

Over a number of decades, it has been known that electromagnetic forming process can improve the performance of material exhibiting in forming. To date, the main factors contributing to the improvement are considered to be: inertia effect, impact collision between the workpiece and mold and the constitutive behavior of materials [3–5,7].

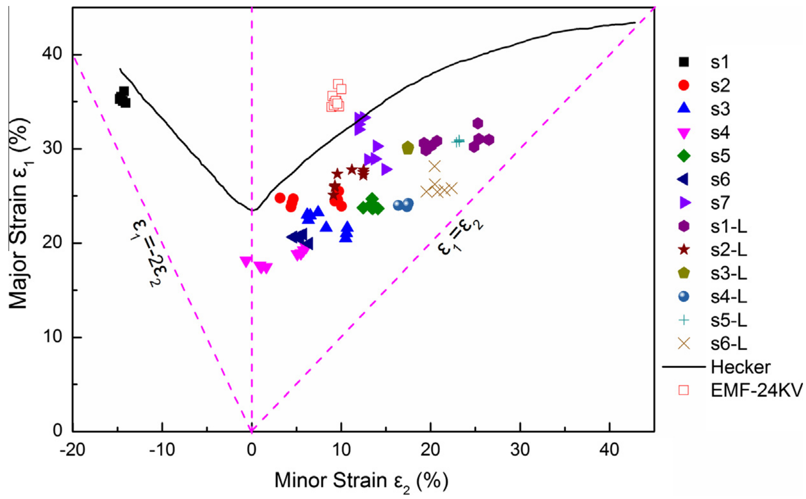

Fig. 11. Combined Erichsen test and EMF formability results for AA5052-O.

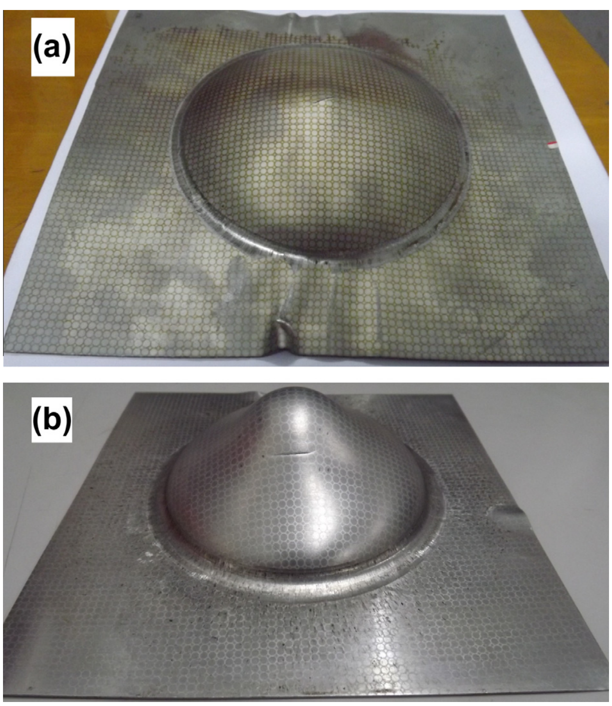

Fig. 12. Two failure models in EMF (a) suffered by Ti–6Al–4V, and (b) suffered by AA5052-O.

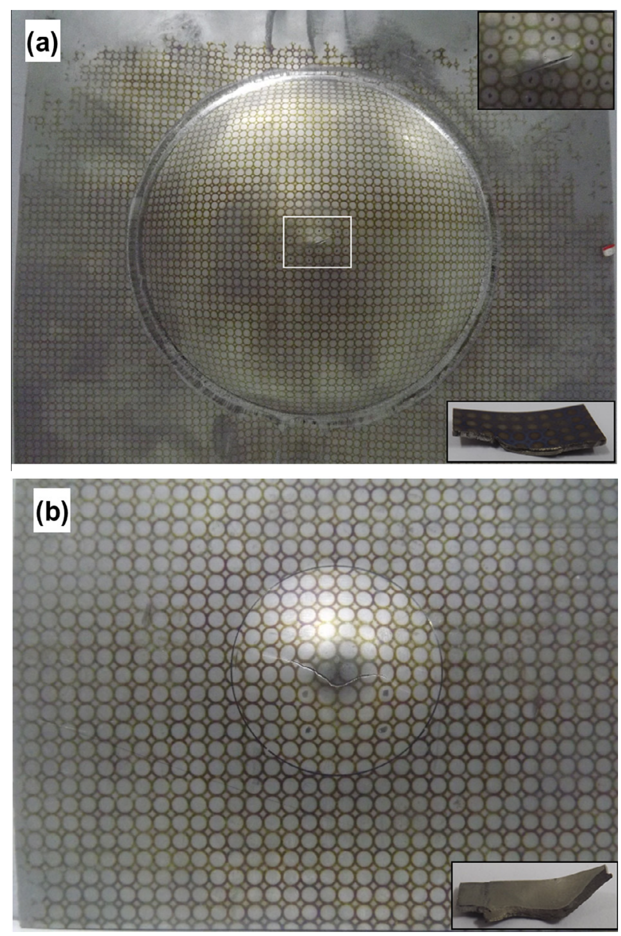

Fig. 13. Crack shapes and fracture macroscopic morphology (a) electromagnetic bulging, and (b) Erichsen test.

Due to the high resistivity of the titanium alloy [18], the induction of eddy current by the coil on the sheet is small, and can be largely ignored. To compensate for this deficiency, an aluminum driver plate was used to force the titanium sheet forming. As a result, the load is a surface force, rather than a body force during the process of forming Ti–6Al–4V. The manner in which the load is applied in EMF using a driver plate is similar to that used in a conventional forming process. According to the literature [25], the temperature rise in one working cycle is insufficient to significantly affect the formability of the material. It is possible to reach the conclusion that the other factors, such as the eddy-induced plasticity of the sheet, the form of the load and the temperature rise contribute little to the extend formability of titanium alloy Ti–6Al–4V in this study.

In electromagnetic free bulging, there is no impact collision between the workpiece and the mold, as described in the literature [7]. But there is an impact between the driver plate and sheet when using the driver plate in sheet metal forming, as described in the literature [9,21]. However, the stress state of the workpiece undergoing forming forced by the driver sheet ($\sigma_1 > 0, \sigma_2 > 0, \sigma_3 < 0$) is different from what occurs when the sheet metal collides with the die ($\sigma_1 < 0, \sigma_2 < 0, \sigma_3 < 0$). According to the well-known J–C damage model, as described in Eq. (1), the crack is suppressed and the

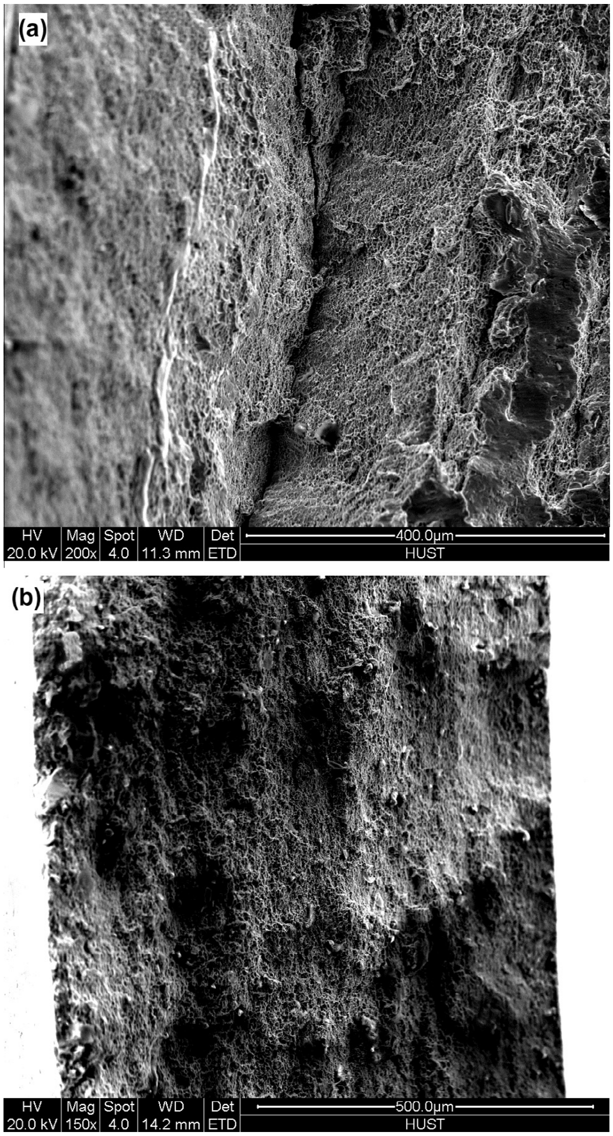

Fig. 14. Scan photos of fractography (a) electromagnetic bulging, and (b) Erichsen test.

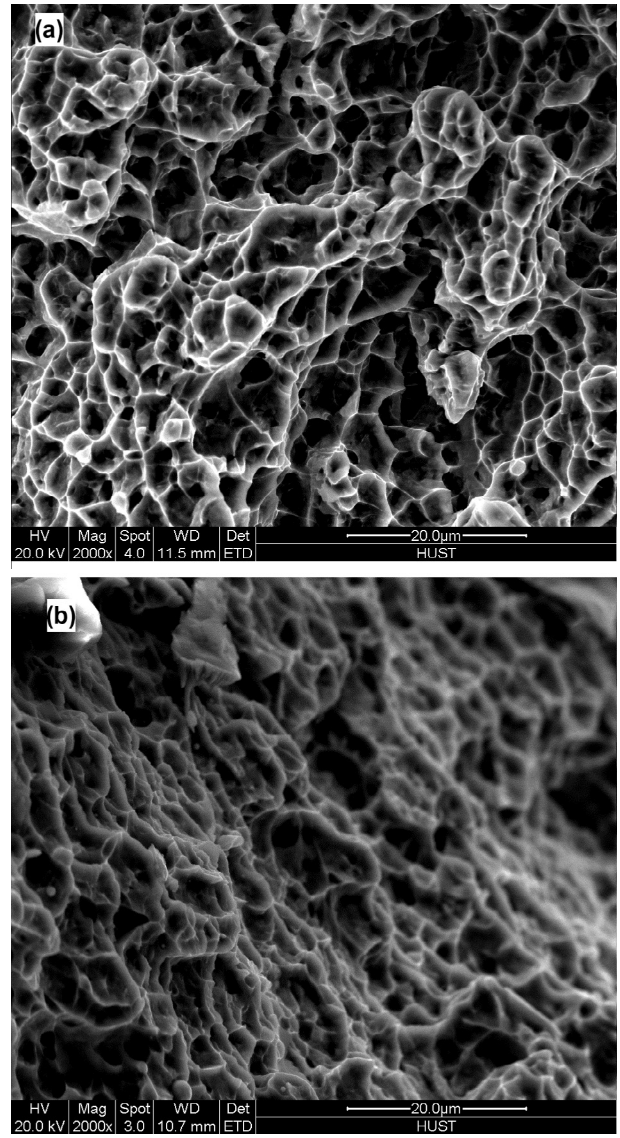

Fig. 15. Scanning topography of fracture region (a) electromagnetic bulging, and (b) Erichsen test.

formability of material can be improved only when the stress triaxiality is negative or exhibiting a triaxial compression stress state. Therefore, we conclude that the impact collision between the driver plate and sheet is not the main factor contributing to the extend formability of titanium alloy Ti–6Al–4V.

$$\varepsilon_f = [d_1 + d_2\ \exp(d_3\eta)]\left[1 + d_4\ \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right][1 + d_5 T^*] \tag{1}$$

where η is the stress-triaxiality factor, defined as the ratio of the hydrostatic stress to the equivalent stress; d_1, d_2, and d_3 are parameters which should be determined from experimental data.

In our previous work, EMF of the titanium plate using a driver sheet was analyzed in detail through a combination of experimental and numerical simulation methods. According to the temperature–pressure-phase diagram of titanium alloy in Ref. [26], the attainable velocity and strain rate of deformation indicates that the constitutive behavior of the material theoretically did not undergo a qualitative change in the level of strain rate. Hence, the inertia effect is considered to be the principle factor contributing to the extension of the forming limit of Ti–6Al–4V in this study.

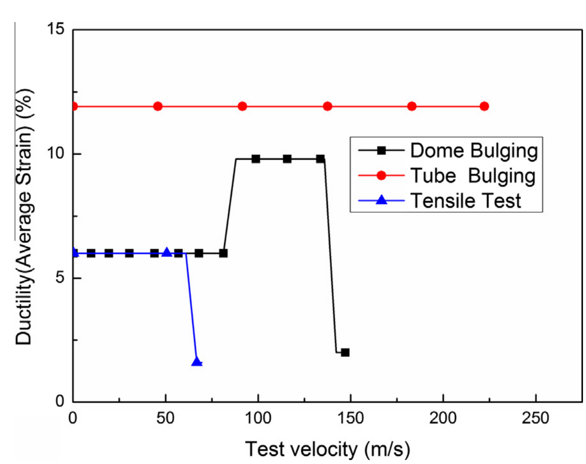

Fig. 16. Ductility vs. test velocity for titanium alloy Ti–6Al–4V.

The Ti–6Al–4V sheet subjected to EMF was first deformed with the aid of the driver sheet and continued to deform and fracture due to the inertia effect. Once the crack appeared, more energy was needed to maintain the expansion of the crack and in order to minimize all the energy in the workpiece, the main crack did not extend fully and divided into the secondary cracks, as shown in Fig. 13a. In the Erichsen test, titanium plates absorbed enough energy to fully extend the crack.

Although Ti–6Al–4V titanium alloy sheet and aluminum sheet fail in the same model in the quasi static condition, the failure models in high strain rate are quite different compared with the results in the Ref. [23]. Using scan photos of fractography, we learned that Ti–6Al–4V titanium alloy sheet fails in a combination of ductile and shear fractures during the electromagnetic bulging process, while only ductile fracture occurs during the Erichsen test. The uniform and deeper dimple in the sheet subjected to EMF indicates higher formability than that found in quasi static forming.

5. Conclusions

The tensile test, Erichsen test (quasi static) and electromagnetic bulging (high strain rate) of titanium alloy Ti–6Al–4V and aluminum alloy AA5052-O were carried out. Forming limits of Ti–6Al–4V and AA5052-O both at quasi static and high strain rate were determined and compared with one another. Then the fracture analyses of Ti–6Al–4V in the two conditions were conducted through SEM. The following conclusions were reached:

(1) The forming limit increased 24.37% for Ti–6Al–4V and only 10.97% for AA5052-O under electromagnetic forming, although the formability of AA5052-O is better than Ti–6Al–4V in quasi static condition.
(2) Different materials have different failure modes when subjected to the electromagnetic forming process. The failure model of Ti–6Al–4V is different from that of AA5052-O under EMF.
(3) According to the fracture analysis of Ti–6Al–4V, the Ti–6Al–4V sheet fails in a combination of ductile fracture and shear fracture during the electromagnetic bulging process while only ductile fracture occurs under the quasi static condition. Improvement in formability is primarily a result of the different fracture behavior due to the inertia effect.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (Grant No. 51175201) and the National Program on Key Basic Research Project (973 Program) of China (Grant No. 2011CB012802). The authors would like to thank Li Qiu (Wuhan National High Magnetic Field Center) for assisting in the experiment, Analysis and Test Center of HUST (Huazhong University of Science and Technology) for using SEM and Myrle Langley for improving the English.

References

[1] Psyk V, Risch D, Kinsey BL, Tekkaya AE, Kleiner M. Electromagnetic forming—a review. J Mater Process Technol 2011;211:787–829.
[2] Mynors DJ, Zhang B. Applications and capabilities of explosive forming. J Mater Process Technol 2002;125–126:1–25.
[3] Balanethiram VS, Daehn GS. Enhanced formability of interstitial free iron at high strain rates. Scripta Metall et Mater 1992;27:1783–8.
[4] Balanethiram VS, Daehn GS. Hyperplasticity: increased forming limits at high workpiece velocity. Scripta Metall et Mater 1994;30:515–20.
[5] Seth M, Vohnout VJ, Daehn GS. Formability of steel sheet in high velocity impact. J Mater Process Technol 2005;168:390–400.
[6] Dariani BM, Liaghat GH, Gerdooei M. Experimental investigation of sheet metal formability under various strain rates. Proc Inst Mech Eng, Part B: J Eng Manuf 2009;223:703–12.
[7] Imbert JM, Winkler SL, Worswick MJ, Golovashchenko S. Formability and damage in electromagnetically formed AA5754 and AA6111. In: Kleiner M. (editor), 1st International conference on high-speed forming. Dortmund; 2004. p. 201–10.
[8] Golovashchenko SF. Material formability and coil design in electromagnetic forming. J Mater Eng Perform 2007;16:314–20.
[9] Li C, Liu D, Yu H, Ji Z. Research on formability of 5052 aluminum alloy sheet in a quasi-static-dynamic tensile process. Int J Mach Tools Manuf 2009;49:117–24.
[10] Oliveira DA, Worswick MJ, Finn M, Newman D. Electromagnetic forming of aluminum alloy sheet: free-form and cavity fill experiments and model. J Mater Process Technol 2005;170:350–62.
[11] Meng Z, Huang S, Hu J, Huang W, Xia Z. Effects of process parameters on warm and electromagnetic hybrid forming of magnesium alloy sheets. J Mater Process Technol 2011;211:863–7.
[12] Xu JR, Yu HP, Li CF. Formability of AZ31 magnesium alloy sheets in Magnetic pulse bulging. Mater Sci Eng: A.
[13] Jimbert P, Ulacia I, Fernandez JI, Eguia I, Gutierrez M, Hurtado I. New forming limits for light alloys by means of electromagnetic forming and numerical simulation of the process. In: 10th Esaform conference on material forming: Part A (AIP conference proceedings volume 907); 2007. p. 1295–300.
[14] Ulacia I, Hurtado I, Imbert J, Salisbury CP, Worswick MJ, Arroyo A. Experimental and numerical study of electromagnetic forming of AZ31B magnesium alloy sheet. Steel research international, vol. 80; 2009. p. 344–50.
[15] Takahashi M, Murakoshi Y, Terasaki M, Sano T, Matsuno KI. Study on electromagnetic forming. V. Free bulging of high-strength-metal plates. II. J Mech Eng Lab (Jpn) 1988;42:1–8.
[16] El-Magd E, Abouridouane M. High speed forming of the light-weight wrought alloys. In: Kleiner M. (editor), 1st International conference on high speed forming. Dortmund; 2004. p. 3–12.
[17] Li F, Mo J, Li J, Zhou H, Huang L. Study on the driver plate for electromagnetic forming of titanium alloy Ti–6Al–4V. Int J Adv Manuf Technol, doi: 10.1007/s00170-013-5002-1.
[18] Larrimer WH, Jr., Duncan DL. Transpactor-a reusable electromagnetic forming tool for high resistivity materials. Tech paper No. MF73-129, Society of Manufacturing Engineers; 1973. p. 14.
[19] ISO 6892:1998(E). Metallic materials—tensile testing at ambient temperature. Switzerland: International Organization for Standardization; 1998.
[20] Xu Z, Cui J, Yu H, Li C. Research on the impact velocity of magnetic impulse welding of pipe fitting. Mater Des 2013;49:736–45.
[21] Li F, Mo J, Zhou H, Fang Y. 3D Numerical simulation method of electromagnetic forming for low conductive metals with a driver. Int J Adv Manuf Technol 2013;64:1575–85.
[22] Hecker SS. Formability of aluminum alloy sheets. J Eng Mater Technol 1975;97:66–73.
[23] Imbert J, Worswick M, Winkler S, Golovashchenko S, Dmitriev V. Analysis of the increased formability of aluminum alloy sheet formed using electromagnetic forming. SAE Trans: J Mater Manuf 2006;114:6–18.
[24] Wood W. Experimental mechanics at velocity extremes—very high strain rates. Exp Mech 1967;7:441–6.
[25] Kuo C-L, You J-S, Hwang S-F. Temperature effect on electromagnetic forming process by finite element analysis. Int J Appl Electrom 2011;35:25–37.
[26] Velisavljevic N, MacLeod S, Cynn H. Titanium alloys at extreme pressure conditions. In: Nurul Amin AKM, editor. Titanium alloys – towards achieving enhanced properties for diversified applications. Shanghai, China: InTech; 2012. p. 67–86.